Behaviour of Doubly-Fed Induction Generators during Grid Faults and the Impact on a Distance Relay

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I. SUMMARY

Since the evolution to big scale wind power plants, wind turbines are also coupled to the transmission grid instead of the distribution grid, causing new protection problems. Problems arise as the short-circuit behaviour of wind turbines equipped with doubly-fed induction generators (DFIG) differs fundamentally from traditional power plants equipped with synchronous generators. When applying a three phase short-circuit at the terminals of the DFIG, the magnetic flux stops rotating and causes a DC-component in the stator. Additional, a DC-component in the rotor arises, causing an AC-component in the stator. In contrast with the three phase fault, the single-line-to-ground fault short-circuits only one phase and keeps the two other phases excited. Due to this excitation, the current amplitudes do not drop to zero in contrast with the three phase fault.

To analyse the influence of DFIGs on the transmission protection, a study case of a wind farm, equipped with DFIGs, in the Belgian grid is considered and analysed in two steps. The first step includes the simulating of short-circuits in a Belgian grid topology with a wind farm. The second step injects the simulations' results in a real distance relay using COMTRADE data exchange. At full load, three phase faults are initially detected but not removed by a distance relay. Single line-to-ground faults are detected and removed correctly when the wind turbines are operating at full load.

The impact of the following parameters is analysed: fault resistance, crowbar resistance, load and number of generators. From this analysis, one can conclude that three phase faults are never removed correctly. A single line-to-ground fault is detected and removed correctly unless the crowbar resistance or the load is lowered. These results confirm that the distance relay with actual settings is not suitable for this grid topology including wind turbines equipped with DFIG.

II. INTRODUCTION

Since the Kyoto commitment is coming closer, renewable energy sources become to present a notable share in the total electricity generating capacity. Moreover, as the European Union has committed to the "20-20-20" initiative, renewable energy sources will have to represent 20% of the total installed capacity in Europe [1]. Wind energy is one of the major contributors to reach these targets. As being widely implemented in the European grid, the major integration of wind energy in power systems embraces different technical, economical and legislative evolutions. This paper focuses on a specific technical issue, i.e. the fault-ride through characteristic.

The first, small-scale, wind turbines were considered to be as a part of distributed energy resources (DER). These sources are traditionally coupled to the distribution grid. The impact accompanied by this integration is studied and analyzed for more than a decade [2][3][4]. With the growing size of wind turbines and wind farms, the coupling of the latter to the transmission grid evolves from exceptional to good practice. This evolution raises the need for better understanding the impact of wind turbines on the transmission grid. One of the critical issues is protection.

As the transmission grid’s protection system differs fundamentally from that of the distribution grid, a new evaluation of the wind energy integration on transmission level is required for protection issues [3]. This paper focuses on one aspect, i.e. distance relaying.

The turbine technology is decisive for the short-circuit behavior, and consequently for detection behavior of the distance relay. Three main wind turbine technologies are currently on the market or yet installed: squirrel cage induction generators (SCIG), doubly-fed induction generators (DFIG) and direct-drive synchronous generators (DDSG). For the latter technology, the behavior both during normal and short-circuit at the grid side is determined by the inverter technology, decoupling the synchronous generator from the grid as illustrated in Figure 1. The inverter current is restricted to the imposed limits due to the small thermal capacity. Contrary to the DDSG technology, the generator of the SCIG and DFIG technology is directly coupled to the grid. Consequently, the short-circuit behavior of the DFIG and SCIG technology depend highly on machine characteristics. The DFIG is partially coupled to the grid through an converter and may lose control if the voltage is out of bounds. This paper contributes to the better understanding of the short-circuit behavior of DFIGs by focusing on protection issues. Contrary to most studies, which only involve three phase faults, this paper also discusses single line-to-ground faults as the latter appear much more frequently in power systems. In a second phase, the impact of DFIGs is evaluated on distance relaying.

Section III discusses first the modeling of wind turbines equipped with DFIGs. Secondly, this section handles the behavior of these generators mainly during short-circuits with the perspective to have this knowledge for a further impact analysis on distance relaying. Section 0 illustrates the problems distance protection faces when implementing DFIGs for a Belgian grid topology. A final section V draws the main conclusions.

III. BEHAVIOUR OF DOUBLY-FED INDUCTION GENERATORS DURING SHORT-CIRCUIT

This section discusses the modeling and behavior of wind turbines during transient, short-circuit, simulations. The first section handles the modeling requirements.

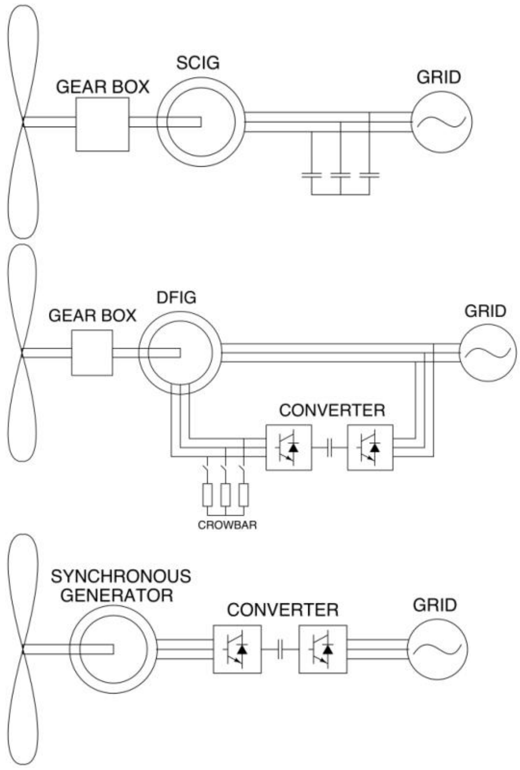

Figure 1: Schematic representation of SCIG (upper scheme), DFIG (middle scheme) and DDSG (lower scheme)

Thereafter, a three phase fault and a single line-to-ground fault are simulated and analyzed with the perspective of the impact on distance relaying. The final subsection discusses the influence of several parameters: crowbar resistance, load and slip. All the simulations are performed with PowerFactory DIgSILENT[1].

A. Turbine modeling

The DFIG wind turbine topology is illustrated in Figure 1 by the middle scheme. This model is implemented in PowerFactory DIgSILENT, which is the power system analysis software used for performing simulations. The short-circuit simulations require the modeling of electrical as well as mechanical components. The mechanical parts involve the propeller, the generator and the coupling in between. Therefore, a two mass model is used [5] to take into account strong torque fluctuations forcing the shaft to behave like a torsion spring.

As already explained in the introduction, the stator of the DFIG is directly coupled to the

[1] http://www.digsilent.de

grid by a three winding transformer. A power converter, scaled to around 30% of the rated generator power, connects the rotor to the grid with an inductance in series. This power converter consists out of a grid side converter and a rotor side converter separated by a DC-bus. In order to protect the converter against high currents or high voltages in case of strong grid transients, a crowbar is implemented. This crowbar short-circuits the rotor windings when high current transients occur by using impedances with a predefined value.

The generator is modeled by a fifth order model [6]. The model equations for this generator are analogous to those of an induction machine. Only the rotor voltages, which are controllable through the converter, differ. As long as grid transients do not produce rotor voltages or currents that exceed the converter limits, this control of rotor voltages is maintained. However, strong grid transients, for instance grid faults close to the generator's terminals, activate the crowbar and generator control is lost. As a consequence, the DFIG is not supplied through two sides, rotor and stator, anymore and behaves like a SCIG. This has major consequences for the power system, as no grid support through the wind turbines is possible. It must be noted that new solutions are being developed to cope with the crowbar problem. These solutions involve the implementation of a chopper in parallel with the DC-bus to avoid high voltages on this capacitance. Those alternatives are not taken into account and will not be further elaborated in this study.

The modeling of wind power plants, containing several wind turbines, can be done through aggregation when simulating the wind farm behavior during grid faults. This choice is justified when using a small wind power plant with negligible cable distances between the wind turbines and with small differences between the different turbine operating conditions. Moreover, the collective impact of the wind power plant on the grid protection is the subject of study and not the individual operating conditions inside the wind farm. This approach of aggregated modeling is validated by former studies [7].

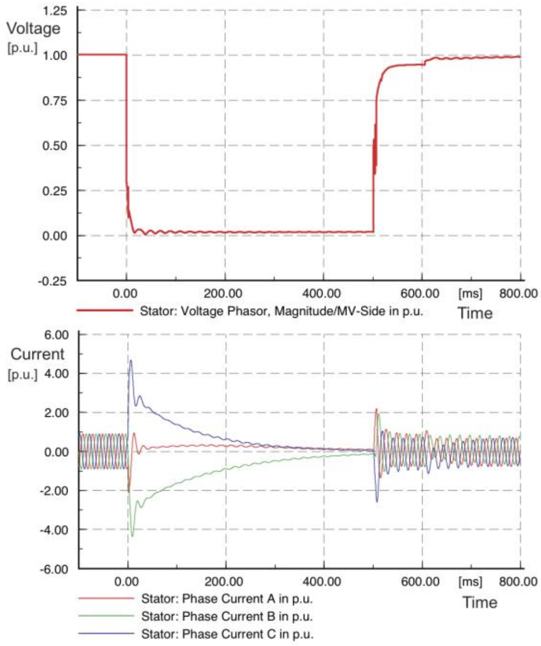

Figure 2: Stator voltage and phase currents during a three phase short-circuit

B. Three phase fault

At time t = 0, a three phase fault with fault resistance R_F = 0.2 Ω is applied at the terminals of the DFIG. Starting from the fault initiation, large oscillating currents appear in the stator. Due to the magnetic coupling between the rotor and stator, large rotor currents are initiated. The converter at the rotor side must be protected and the crowbar is activated very shortly after the fault because of the rapid voltage increase on the DC link in between the two converters. The fault duration is 500 ms and the crowbar is removed after a predefined time period of 100 ms after the fault removal.

The stator voltage and phase currents are illustrated in Figure 2. The shape of the voltage and phase currents is essential for the protection system. Due to the short-circuit, the flux stops rotating and causes a DC-component in the stator. Secondly, a DC-component is excited in the rotor, which in turn results in a AC-component in the stator. The latter has a significantly lower time constant compared to the DC-current in the stator. Consequently, the AC current in the stator is quickly damped and a DC current remains. This DC current drops to zero because almost all excitation is lost due to the dramatic voltage drop to a value close to zero.

C. Single line-to-ground fault

Again at time t = 0, a fault with resistance R_F = 0.2 Ω is applied at the terminals of the DFIG. In contrast with the three phase fault, the single line-to-ground fault short-circuits only one phase and keeps the two other phases excited. Due to the remaining excitation, the stator current amplitudes do not drop to zero. The short-circuited phase shows a similar behavior to the phase currents of the three phase fault. Both a DC component and a fast decaying AC component occur in the stator current. However, the two healthy phases influence the short-circuited phase through the magnetic coupling.

D. Parameter analysis

This section discusses the influence of the following parameters: crowbar resistance, load and slip. Both the current and the generator speed are analyzed.

1) Crowbar resistance

The influence of the crowbar resistance R_{cb} is studied by comparing three identical generators with different resistance values:

- Generator 1: R_{cb} = 0.05 p.u.
- Generator 2: R_{cb} = 0.1 p.u.
- Generator 3: R_{cb} = 0.5 p.u.

The fault is applied at t = 0 and cleared after 200 ms. The crowbar is removed 300 ms after the fault initiation. Because the rotor and stator currents are very similar due to the magnetic coupling, the crowbar has a significant influence on the stator currents. From Figure 4, one can conclude that for three phase faults:

- when activating the crowbar, a higher crowbar resistance damps the initial current peak more,
- a higher resistance lowers the time constant of the rotor DC component resulting in fast decaying of the AC component in the stator,
- The generator with the highest resistance has the highest current on the moment that the fault is cleared,
- After removing the fault, a higher resistance damps the current transients the most.

During the fault, a high resistance damps the active and reactive power. Moreover, a higher resistance value has a positive influence on the torque versus rotation characteristic and the generator will accelerate less rapidly. Figure 3 illustrates this phenomenon. After the fault is cleared, a high resistance causes high oscillations. Although high resistance values improve the stability during faults, the post-fault stability is deteriorated. This points out the significance of calculating a well-considered resistance value.

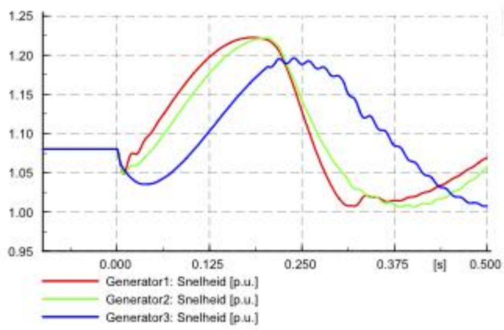

Figure 3: Generator speed with varying crowbar resistance during a three phase fault

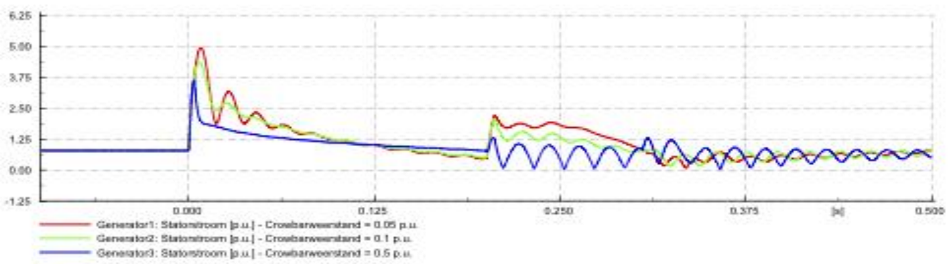

Figure 4: Stator current with varying crowbar resistances for a three phase fault

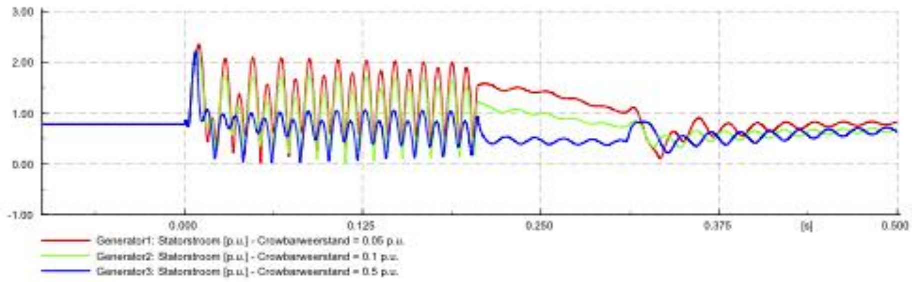

Figure 5: Stator current with varying crowbar resistance during a single line-to-ground fault

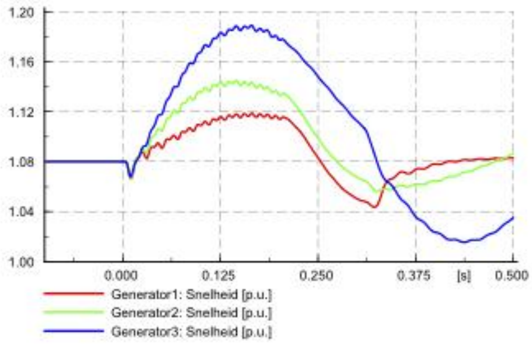

Figure 6: Generator speed with varying crowbar resistance during a single line-to-ground fault

For a single line-to-ground fault, the varying resistance shows similar impacts on the current shown in Figure 5. Moreover, the stationary currents are damped due to a higher resistance. The speed progress in time is different from a three phase fault. Figure 6 illustrates that generator 3 has the largest acceleration. The high resistance limits the rotor and stator currents the most creating a lower electrical torque. Due to the constant mechanical torque, the torque difference becomes higher and the shaft relaxes more resulting in higher speeds. It is interesting to note that a high resistance value is favourable for speed variations during three phase faults, but not during single line-to-ground faults.

2) *Load and slip*

Again, three identical generators are compared but with different active power *P*, reactive power *Q* and slip *s:*

- Generator 1: *P* = 0.3 MW *Q* = 0.01 MVar *s* = -15 %,
- Generator 2: *P* = 3 MW *Q* = 0.1 MVar *s* = 0 %
- Generator 3: *P* = 4.5 MW *Q* = 0.2 MVar *s* = 10 %.

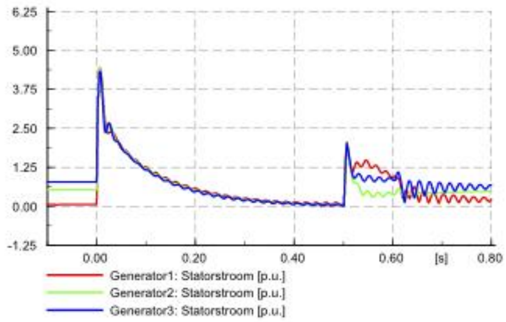

Figure 7: Stator current with varying load and slip during a three phase fault

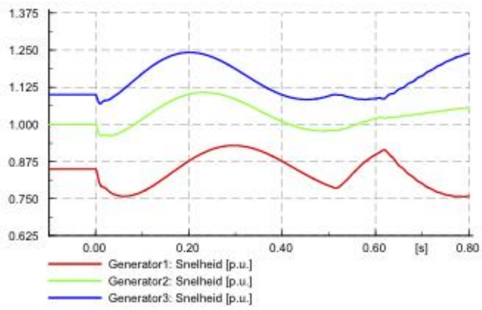

Figure 8: Generator speed with varying load and slip during a three phase fault

Figure 7 illustrates the stator currents for the three generators. The fault is applied at *t* = 0 and cleared after 500 ms. The crowbar is removed after a predefined period of 600 ms after the fault initiation. No remarkable distinctions are apparent. Because the current of generator 1 is smaller in the pre-fault situation, this generator reaches the peak current later and the crowbar is activated later compared with generator 3. The difference in peak current is 8 %.

The generator speeds are shown in Figure 8. The speed drop for generator 1 and 2 is larger because the mechanical torque is lower for

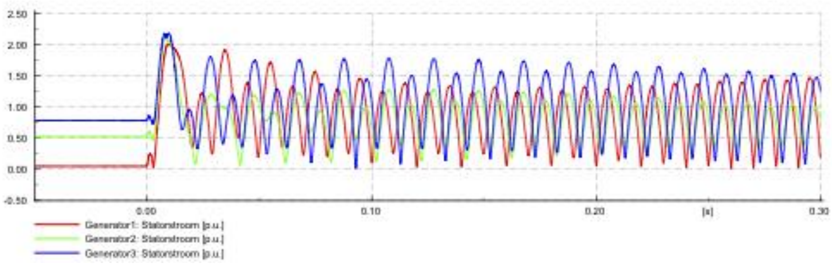

Figure 9: Stator current with varying load and slip during a single line-to-ground fault

these generators. After the fault clearing, generator 1 is working at subsynchronous speed. The generator behaves as an induction motor and demands active and reactive power. The generator accelerates towards the synchronous speed.

The currents for a single line-to-ground fault are illustrated on Figure 9. The current amplitudes depend on the active and reactive power exchanged. Generator 1 has a negative slip value during the fault and the active power is negative. Generator 2 has the smallest current and a slip value close to zero.

IV. IMPACT ON A DISTANCE RELAY: A STUDY CASE

This section handles about the impact of a wind power plant equipped with DFIGs on distance relaying in a Belgian grid topology. In a first subsection, the methodology for the simulations is described including the test setup. Secondly, the grid topology is explained. In a final subsection, simulation results are discussed starting from a base case both for the three phase fault and the single line-to-ground fault and ending with a brief discussion about the impact of varying parameters.

A. Methodology

This section describes the approach used in order to analyze the impact of DFIGs on distance relaying. Figure 10 illustrates the full approach. Transient simulations are performed with three phase faults as well as single line-to-ground faults. The study of this short-circuit behavior of wind turbines, performed in the former section, is essential for further analysis. The second input for simulations implies the grid topology. Therefore, a Belgian grid topology is implemented, including the integration of a wind power plant equipped with DFIGs. The grid topology is illustrated in Figure 11. The distance relay under consideration is marked with symbol A. Almost all faults are applied at the HV bus. A third input considers the following parameters: fault resistance, crowbar resistance, wind power and number of generators.

Using these inputs, EMT simulations are performed using DIgSILENT. From these simulations, the current and voltage signals at the distance relay location from all three phases are recorded. These digital signals are transformed into analog current and voltage signals and are injected in a real distance relay. From this distance relay, all event information is withdrawn for analysis. The authors have chosen for this approach to avoid the difficult modeling of distance relays. Moreover, actual relay settings of an industrial device that is being used in the field, give much more realistic results and avoid the gap between model and device.

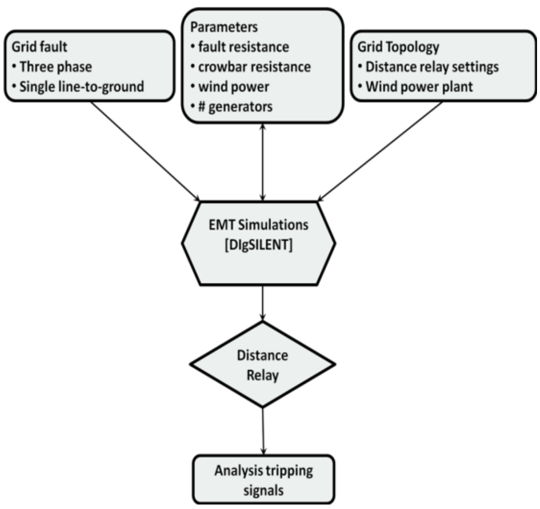

Figure 10: Schematic representation of the methodology

B. Grid topology

The topology of the grid is illustrated in Figure 11. Six wind turbines, each with a capacity of 5 MW, are connected to the MV bus. This bus is connected to the transmission grid at 150 kV through transformer T. The transmission grid at that point has a short-circuit power S_{sc} = 5.2 GVA. The short-circuits studied are always applied at the HV bus.

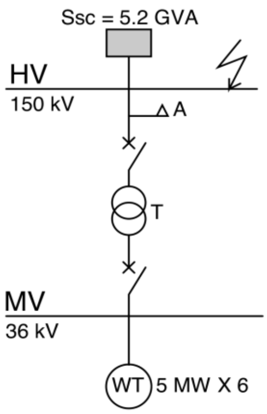

Figure 11: Grid topology

Figure 12 gives a schematic overview of all operating zones with delay times of the distance relay under consideration. The HV bus at which faults are applied is called HV_{from} in this figure. Consequently, these faults are located in the forward direction of the distance relay. Assuming faults on the HV bus, the bus differential protection is the primary protection system. In case of failure, distance relay A acts as a backup protection system for faults on the HV bus, and needs to disconnect the line from the bus. If the relay functions correctly, it detects the fault on the bus and trips after a predefined delay time of 500 ms. In that way, sufficient time is given to the primary protection to operate correctly. To summarize, the distance relay has three zones in the forward direction and two zones in the backward direction, each with a different time delay for operation.

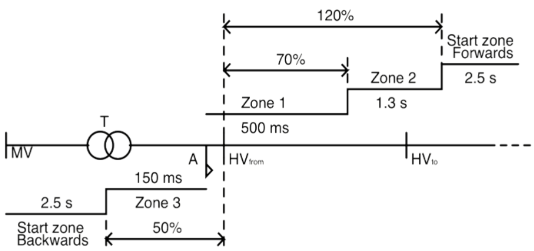

Figure 12: Distance zones with delay times

C. Simulation results

This section gives the simulation results. Two base cases are defined both for the three phase and single line-to-ground fault. In a final section, a parameter analysis is performed.

1) Three phase fault

Before the fault is applied, each DFIG is producing 4.5 MW and 0.2 MVar. The generator speed is 1.08 p.u. The detection time is represented by the pick-up time (PU time). The detection behavior can be described as follows. After the fault initiation, the relay detects the fault in the forward direction due to the high current peak as illustrated in Figure 2. After 34 ms, the current drops to a value below 0.2 A (on the secondary side of the measuring transformer), resulting in an interruption of the detection. From this observation, one can conclude that the relay detects the fault initially but fails to remove the fault after the predefined time of 500 ms. This due to the current value which becomes too small for correctly defining the line impedance and detecting the fault location.

2) Single line-to-ground fault

The relay detects the fault correctly in the forward direction. Although the distance relay detects the fault several times during short time periods in the backward direction, the relay operates correctly. The relay tolerates short interruptions of the detection in a zone by using a memory. Contrary to the three phase fault, a single line-to-ground fault is detected and also removed correctly.

3) Parameter analysis

This section handles about the impact of varying parameters on the distance relay. The parameters involved are: crowbar resistance, fault resistance, load and number of generators. The results are summarized in Table 1. Each parameter is individually raised or lowered in comparison to the base case. This results in three possible scenarios, defined in the legend.

The impact of the crowbar resistance is of major importance. The relay behavior changes from detection to no detection. Due to the higher crowbar resistance, the peak current is lowered, as discussed in the former section, and detection of the fault is prevented. Consequently, the quick insertion of the crowbar impacts the fault detection significantly. A lower crowbar resistance causes an unpredictable detection behavior of the relay due to a switching detection between the forward and backward direction. The crowbar resistance determination is often a matter of stability. However, this determination also impacts the distance relay detection.

Parameter	Three phase fault		Single line-to-ground fault	
	Low	High	Low	Hig
Base case	D/NR		D/R	
Crowbar resistance	D/NR	ND	D/R	ND
Fault resistance	D/NR	ND	D/R	ND
Wind power	ND	D/NR	ND	D/R
# Generators	ND	D/NR	D/R	D/R

LEGEND	
Symbol	Definition
D/R	*Fault detected and removed*
D/NR	*Fault detected but not removed*
ND	*Fault not detected*

Table 1: Summary of parameter analysis

The second parameter's, fault resistance, influence is decisive for the detection behavior. Raising the fault impedance lowers the detected short-circuit current and pushes the calculated impedance down. A larger impedance measured by the distance relay implicates a fault in an operating zone further than zone 1, the zone under consideration. Thereupon, detection is prevented.

The final two parameters from Table 1 have a similar impact. Lowering the load results in a smaller current peak. As a consequence, the fault remains undetected. The same result applies for lowering the number of generators. The smaller the number of generators, the smaller the demagnetization which is responsible for the high current peak.

V. CONCLUSION

Firstly, one can conclude that for a grid fault close to the generator, control is lost and the interaction with the grid is determined by the machine characteristics (crowbar resistance) and the operating point (load and slip).

Secondly, the impact of a wind power plant using doubly-fed induction generators on a distance relay is studied. In case of a three phase fault, the detection is interrupted due to small currents resulting from the loss of excitation. A single line-to-ground fault is detected and removed correctly unless the crowbar resistance or the load is lowered. A higher number of generators increases the short-circuit power and has a positive influence on the detection behavior. A lower crowbar resistance causes an unpredictable detection behavior resulting in a backward detection and an early, incorrect fault removal.

From these results, one can conclude that this distance relay with its actual settings is not suitable for this grid topology including wind turbines equipped with DFIG. Further research should focus on this problem and suggest possible solutions. Moreover, other wind energy conversion systems like the direct-drive synchronous generator should be included in further research as the behavior of this technology differs fundamentally from the doubly-fed induction generator.

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